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LUNAR PHYSICAL PATAMETERS STUDY

PARTIAL REPORT NO. 7

MEASUREMENT OF ELECTRICAL PROPERTIES

ON LUNAR SURFACE - A FEASIBILITY STUDY

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1 of 31

LUNAR PHYSICAL PARAMETERS STUDY

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MEASURMENT OF ELECTRICAL PROPERTIES ON LUNAR SURFACE

A FEASIBILITY STUDY

December 15, 1960

TEXACO
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3

LUNAR PHYSICAL PARAMETERS STUDY

MEASUREMENT OF ELECTRICAL PROPERTIES

TABLE OF CONTENTS

LUNAR PHYSICAL PARAMETERS STUDY

MEASUREMENT OF ELECTRICAL PROPERTIES

A FEASIBILITY STUDY

I. INTRODUCTION

Several methods to determine the magnetic susceptibility of earth formations in situ have been used in geophysical exploration and have been reported in the literature. For measurements on the lunar surface, the method of the induction balance as used by Harold M. Mooney[1] was selected since this method promises the best elimination of the errors introduced by surface irregularities.

The object of this report is to present the experimental results, and to show that theoretical calculations are in good agreement with these results. By using coil dimensions determined through theoretical means it is possible to show that an arrangement exists which will have a minimum error when placed on the lunar surface having specified surface irregularities.

II. THEORY

The principle underlying the use of an induction-balance for the measurement of magnetic susceptibility is that any material brought into the magnetic field of the balance will change the mutual inductance between two coils. This change in mutual inductance represents the change in magnetic susceptibility in the field of the balance. The mutual inductance change with respect to vacuum is a direct measure of the magnetic susceptibility.

[1] Harold M. Mooney, "Magnetic Susceptibility Measurement in Minnesota; Part I, Technique of Measurement", Geo. Vol. 17, 1952, pp 531-543

The inductance-balance described here for the measurement of the magnetic susceptibility of the lunar surface material consists of a three coil arrangement.

The three coils of the induction balance are shown in Fig. 1. The mutual inductance between Coil C and Coil A and B is the difference between the mutual inductance of the coil pairs, A - C, and B - C, since the current paths in A and B are in opposite directions.

The mutual inductance (M) of a coil pair in a vacuum (Susceptibility K = 0) can be expressed by the equation[2]:

$$M = \frac{8\pi \quad n_1 n_2 \quad \sqrt{r_1 r_2} \quad (1-t^2/2)(K(t)-E(t)) \times 10^{-9}}{t} \qquad (1)$$

M = Mutual Inductance (henries)

n = Number of turns of wire

r = Radii (cm) of coils

K(t) and E(t) are complete elliptic integrals of the first and second kind

$t^2 = 4\ r_1 r_2/(r_1 + r_2)^2 + h^2$

h = Axial offset of coils - (cm)

Subindeces 1 and 2 refer to the individual coils.

The change in mutual inductance (ΔM) and in self inductance (ΔL) due to a change in media below the coils can be calculated by using the images of the coils in the media[3]. By using

[2] William R. Smythe, "Static and Dynamic Electricity", Second Edition, McGraw Hill, 1950, pp 313

[3] Ibid, pp 286

equation (1) the change in mutual inductance ΔM_{CA} of Coil C on the Coil A can be calculated by making h equal the distance between C and the image of A. A repeat of the above calculation making h equal to the distance between C and the image of B and taking the difference of the two values will give the change in mutual inductance of the two coils on Coil C. This value will be designated G_1 in this paper. In the same manner the change in self-inductance (ΔL) can be determined by making h equal to the distance between Coil C and its image in the media. This value will be designated G_2 in this paper. The image strength will depend on the susceptibility (K) of the media and is equal to $2\pi K/1+2\pi K$,

hence,

$$\text{a)} \quad \Delta M = G_1\left(\frac{2\pi K}{1+2\pi K}\right) = (\Delta M_{CB} - \Delta M_{CA})\left(\frac{2\pi K}{1+2\pi K}\right) \qquad (2)$$

$$\text{b)} \quad \Delta L = G_2\left(\frac{2\pi K}{1+\pi K}\right) = \Delta L_C \left(\frac{2\pi K}{1+2\pi K}\right)$$

To measure these changes in mutual inductance a Carey-Foster[4] bridge was selected. Fig. 2 is a sketch of the circuit used in the experiments. The balance conditions of this bridge are as follows:

$$\text{a)} \quad R_1 = \frac{M}{CR_2} - R_C \qquad (3)$$

$$\text{b)} \quad R_3 = R_2 \frac{L_C - M}{M}$$

where,

R_C = Resistance of Coil C

[4] Melville B. Stout, "Basic Electrical Measurements", Prentice - Hall, Inc., pp 240

L_C = Self-inductance of Coil C (henries)

M = Mutual inductance of coil arrangement (henries)

R_2 = 100 ohms

R_1 = 0 - 1000 ohms, variable in steps of 0.05 ohm

R_3 = 0 - 80 K ohms, variable in steps of 1 ohm

C = 0.01 microfarad

The relationship of a change in coil characteristics M, L_C and R_C to the resulting change in the bridge balance can be obtained by differentiation of equation (3a) and (3b) with respect to M, L_C and R_C. The following equations show this relationship.

$$\text{a)}\quad \frac{\Delta R_1}{R_1} = \frac{\Delta M - R_2 C\, \Delta R_C}{M - R_2\, C R_C} \tag{4}$$

$$\text{b)}\quad \frac{\Delta R_3}{R_3} = \frac{M\, \Delta L_C - L_C\, \Delta M}{M(L_C - M)}$$

Where ΔR_C and ΔM are the changes of the coil characteristics due to the conductivity and susceptibility, respectively, of the media brought into the field of the coil arrangement.

since, $L_C \gg M$ the equation (4b) reduces to

$$\frac{\Delta R_3}{R_3} = \frac{\Delta L_C}{L_C} - \frac{\Delta M}{M} \tag{5}$$

Elimination of L_C in equation (5) with the balance condition (3b) and substitution of G_1 and G_2 into equation (5) using equation (2a) and (2b), we obtain our final relationship between susceptibility and the bridge balance condition.

$$\Delta R_3 = R_3 \frac{G_2 - (1 + \frac{R_3}{R_2})\, G_1}{M(1 + \frac{R_3}{R_2})} \frac{2\pi K}{1 + 2\pi K} \tag{6}$$

$$= \frac{2\pi K}{1 + 2\pi K} F(G_1, G_2, R_2, R_3)$$

The function $F = F(G_1, G_2, R_2, R_3)$ is mainly dependent on G_1, since $R_3 \gg R_2$ and since G_2 drops off sharply by raising the arrangement above the surface of the material of which K is to be determined. F is solely a function of the geometry of the coil arrangement and the relative position of this arrangement to the surface of the material. It is seen from equation (6) that ΔR_3 is a linear function of the susceptibility at a constant F and for a wide range of K.

Therefore, to compare different coil arrangements with respect to height above the surface only F or G_1, respectively, need to be evaluated.

Of interest is that this particular method will not result in an independent measurement of the conductivity as seen from equation (4a) except under certain conditions. The measurement of ΔR_C is not independent of that of ΔM.

However, ΔR_C may be obtained by substituting $\frac{\Delta M}{M} = -\frac{\Delta R_3}{R_3}$ into equation (4a). This relationship for $\frac{\Delta M}{M}$ is from equation (5) when it is assumed that $\frac{\Delta L_C}{L_C}$ is small compared to $\frac{\Delta M}{M}$. This is valid for distances larger than 1 - 3 cm. from the surface. The following equation is obtained for ΔR_C,

$$\Delta R_C = -\left[\frac{\Delta R_C}{R_3} + \left(\frac{M}{M - R_2 C R_C}\right)\left(\frac{\Delta R_1}{R_1}\right)\right] \frac{M}{CR_2} \tag{7}$$

In principle all the factors in equation (7) are known or measured. However, in practice, this requires resistivities of the adjacent material to be lower than approximately 10 - 100 ohm-cm.

III. THEORETICAL CALCULATIONS

To find a coil arrangement which will operate satisfactory at an elevation of approximately 10 cm. above the surface to be measured and to compensate for surface irregularities, computer computations were made using different coil arrangements. The computations for a change in mutual inductance (ΔM) were made using equation (2a) with unit turns on each set of coils, and when plotted were normalized to a zero value of ΔM at zero elevation from the surface.

In Figs 3 through 11 the change in mutual inductance of each coil pair was plotted versus the elevation of the coils above the surface. The difference of these two curves is G_1, which is also plotted in the figures. It is seen that G_1 has a maximum at a distance from the surface. The elevation at which this maximum occurs and the width of the maximum of G_1 determines the optimum coil arrangement needed to minimize the effect of the specified irregular lunar surface conditions.

Table I shows the elevation at which the maximum of G_1 occurs, and the elevation interval at which G_1 is greater than 90%, 80% and 70% of its maximum value. From Table I it is seen that the figures can be placed in three groups;

Group 1 - Coil A, which is variable in radius is located 2 cm. axially above a coplanar arrangement of Coil B and Coil C.

Group 2 - Coil A, which has a constant radius is located axially a variable distance above a coplanar arrangement of Coil B and Coil C.

Group 3 - Coil A and Coil B with variable radii in a coplanar arrangement with Coil C.

In Group 1, as shown in Table I, it can be seen that as the radius of Coil A increases there is an increase in the elevation at which the maximum of G_1 occurs, there is also an increase in the interval at which G_1 is 90% of its peak value. Using coils of this group to measure the susceptibility of the lunar surface, an error of 10% exists over the elevation range of 2.5 cm. to 5.0 cm.

In Group 2 an increase in the distance of Coil A from the coplanar arrangement of Coil B and Coil C causes a decrease in the elevation at which the maximum of G_1 (G_1 max.) occurs. This decrease indicates that a coplanar arrangement of all coils should be the better of the three groups.

Group 3 shows a wide range of elevations at which G_1 max. occurs. It can be seen that in the coplanar arrangement the lowest elevation at which the maximum G_1 occurs is higher than that of any arrangement of the other groups. It was found that the best arrangement exists when the radius of Coil A approaches that of

11

Coil B. An increase in the radii of both Coils A and B leads to an elevation which will enable the measurement of the susceptibility of a material having surface irregularities specified to exist on the lunar body, i.e., 10 cm. protuberances. With a coil arrangement as shown in Fig. 11 it is possible to measure the susceptibility to within $\pm$ 15% if the coil is placed within a distance of 5 to 16 cm. from the plane of the main body.

IV. EXPERIMENTAL RESULTS

Two coil arrangements were built by the laboratory and tested. The first arrangement tested consisted of;

Coil B - Radius = 15.2 cm. with 365 turns of wire

Coil C - Radius = 5.0 cm. with 500 turns of wire

Coil A - Radius = 5.0 cm. with 500 turns of wire

Coil A is located a distance of approximately 5.0 cm. axially above the coplanar arrangement of Coil B and Coil C. The wire used was No. 29 Formex copper wound on spools made of plexiglass. Three legs were placed in the outer edge of the larger coil to enable adjustments in height above the surface of the material to be measured. Tests were made using a solution of $FeCl_3$ in water as a susceptibility standard. The volume susceptibility of the standard was 80.0×10^{-6}, c.g.s. units. The solution was placed in a wooden box 3'x3'x1' and readings were taken at intervals from zero to 10 cm. elevation. Fig. 12 is a plot of the ΔR_3 readings versus elevation. Fig. 13 is a plot of ΔR_3 made with the same coplanar arrangement of the above experimental coil with the exception that Coil A was increased in radius to 15.2 cm. with 440 turns of wire.

Table II shows the elevation at which a maximum ΔR_3 occurs, and the elevation interval at which ΔR_3 is greater than 90% of its maximum value for the two experiments. A comparison between Table I and Table II shows that the theoretical calculations and experimental results are in good agreement.

Therefore, the assumption can be made that theoretical calculations can be used to accurately determine the geometry and size of the coil arrangement for optimum performance over specified surface conditions.

Using equation (3a) it is possible to determine the value of M for the experimental coils. For the coil arrangement shown in Fig. 12, using the resistance of the wire wound on Coil C equal to R_C, M was found to equal 400 microhenries. Placing the coils over a solution of $FeCl_3$ ($K = 80 \times 10^{-6}$ c.g.s. units) caused a change in M of 7.0 microhenries. Therefore, it can be assumed that a change in mutual inductance of approximately .1 microhenry for each 1×10^{-6} c.g.s. unit exists.

Laboratory data were taken using coil forms made of plexiglass. This type of coil form is subject to stresses and elongations caused by changes in temperature, and without suitable thermal insulation about the coil forms accurate readings could not be made.

V. DISCUSSION

The experimental results obtained by the laboratory indicate that they are in good agreement with theoretical calculations. Theoretical calculations show that a coplanar coil arrangement having a maximum radius of 25 cm. will make susceptibility measurements to within ± 15% if the coil is placed within a distance of 5 to 16 cm. from the average of all protuberances. The wire weight, using aluminum wire, would be 500 grams for this coil arrangement with Coils A, B, and C having 20, 25, and 5 cm. radius, respectively, and 90, 110, and 250 turns of No. 29 wire, respectively.

The coil spools should be made of a material which has a much lower coefficient of thermal expansion than the plexiglass spools used in the experimental model. Measurements made with these coils in the laboratory required an environment of constant temperature, but most of the causes for temperature variations in the laboratory experiments (sun going behind cloud, wind) will be absent in the lunar environment.

The linear range of the inductance balance method of determining susceptibility is from 0 to 10,000 x 10^{-6} c.g.s. units. At susceptibilities above these values demagnetization effects must be taken into account[5]. A calibration curve can be made which enables susceptibility measurement to 100,000 x 10^{-6} c.g.s units.

The measuring coils should be used approximately 4 feet from large metal objects. This minimum distance can be varied dependent upon the mass and size of these objects.

VI. CONCLUSIONS

1. A device to measure the susceptibility of the lunar surface can be designed which will measure within an error of ± 15%

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[5] K. Puzicha, "Magnetism of Rocks as a Function of Magnetic Content", Beitr. Ang. Geoph., 9, 2 (1941), pp 158-186.

under specified conditions.

2. The weight of the wire used for the coils will be approximately 500 gms.

3. Spool material must have: low coefficient of expansion, high strength, and low specific weight.

4. Coils must be rigidly mounted so that no deformation can occur between measurements.

5. A calibration curve can be established which will enable measurements of susceptibility over the range from 0 to $100,000 \times 10^{-6}$ c.g.s. units.

6. With this coil arrangement it is not practicable to measure conductivity in the range of interest.

7. To eliminate the influence of metal objects the coil arrangement should be kept well away from any such objects. The permissible distance is governed by the mass and shape of the metal body.

VII. ELECTRICAL RESISTIVITY

As was shown in the previous sections, it is not practical to measure resistivities within the range expected to be encountered using the three coil arrangement. A detail discussion of this is given in Partial Report No. 6, "Feasibility of Downhole Logging Tool." In this discussion, it was pointed out that the basic reason is that the Q of this inductive circuit is too low, and that to measure high resistivities by inductive means, it is necessary to have a high Q coil. Experimentally, it was found that an air core coil (6 turns of No. 16 wire) wound around the legs of the apparatus shown in Fig.

2 (illustrated as Coil D) had a Q of 180 at 10 megacycles. As shown by experiment in Partial Report No. 6, by measuring the decrease in Q from a vacuum condition, resistivities between 10^1 - 10^{12} ohm-cm. could be measured with a coil having a Q of 159. The large diameter coil would be necessary to minimize the effects of surface irregularities and to minimize the effect of variations in z. Also, as was pointed out in Partial Report No. 6, the Q of a coil may be raised several orders of magnitude by using a negative resistance circuit, so that the range of measurement could be extended considerably. In Partial Report No. 6 it was pointed out that the range of resistivities of the lunar material may be several orders of magnitude higher than 10^{10} ohm-cm.

The conclusion is that the resistivity should be measured by measuring the Q of a coil. The wire on the coil would weigh approximately 1 ounce.

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TABLE I

(Table showing elevation for G_1 maximum and elevation interval for $G_1 \geq$ 0.9, 0.8 and 0.7 times G_1 maximum.)

Group No.	Coil Arrangement (cm) r_a	r_b	r_c	h	Elevation at G_1 Max. in cm.	Elevation Interval (cm) at Which G_1 is: 0.9xG_1 Max	0.8xG_1 Max	0.7xG_1 Max	Fig. No.
1	4	15	5	2	2.0	0.8 - 3.3	--	--	3
	10	15	5	2	3.25	2.4 - 4.9	2.0 - 5.9	1.6 - 6.9	4
	15	15	5	2	3.50	2.4 - 4.9	1.8 - 5.4	1.2 - 6.5	5
2	15	15	5	2	3.50	2.4 - 4.9	1.8 - 5.4	1.2 - 6.5	5
	15	15	5	5	3.0	2.04- 4.3	1.7 - 4.9	1.4 - 5.6	6
	5	15	5	5	3.0	1.9 - 4.4	1.5 - 5.1	1.12- 5.9	7
	4	15	5	2	2.0	0.8 - 3.3	--	--	1
	4	15	5	0	3.6	2.5 - 5.0	2.0 - 5.8	1.8 - 6.4	8
3	4	15	5	0	3.6	2.5 - 5.0	2.0 - 5.8	1.8 - 6.4	8
	10	15	5	0	4.5	2.9 - 5.6	2.6 - 5.9	2.2 - 6.5	9
	12.5	25	5	0	7.0	4.0 -10.4	--	--	10
	20	25	5	0	9.0	6.3 -11.1	5.3 -12.5	4.9 - 16	11

17

TABLE II

(Table Showing Elevation for ΔR_3 Max. and Elevation Interval for $\Delta R_3 \geq 0.9$ times ΔR_3 Max.)

Medium $FeCl_3$, $K_{vol.} = 80 \times 10^{-6}$ c.g.s. units, R_3 = 70K ohm for $K_{vol.} = 0$

Coil Arrangement r_a in cm	r_b	r_c	h	Elevation at ΔR_3 Max. in cm.	Elevation Interval at which $\Delta R_3 \geq 0.9 \times R_3$ Max. in cm.
5	15.2	5	5	3.3	2.0 - 5.1
15.2	15.2	5	5	3.0	1.7 - 4.3

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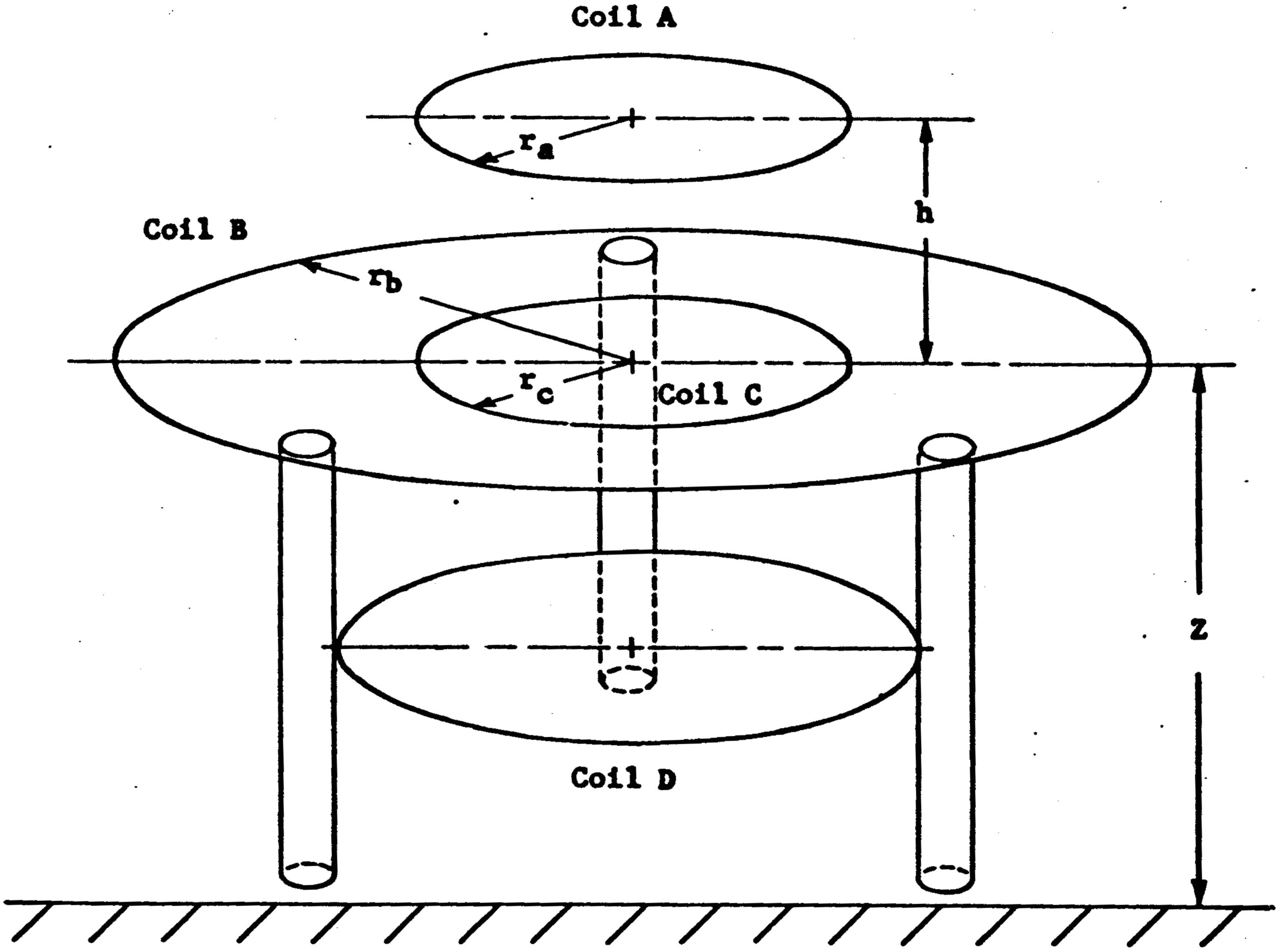

FIGURE 1

ARRANGEMENT OF COILS

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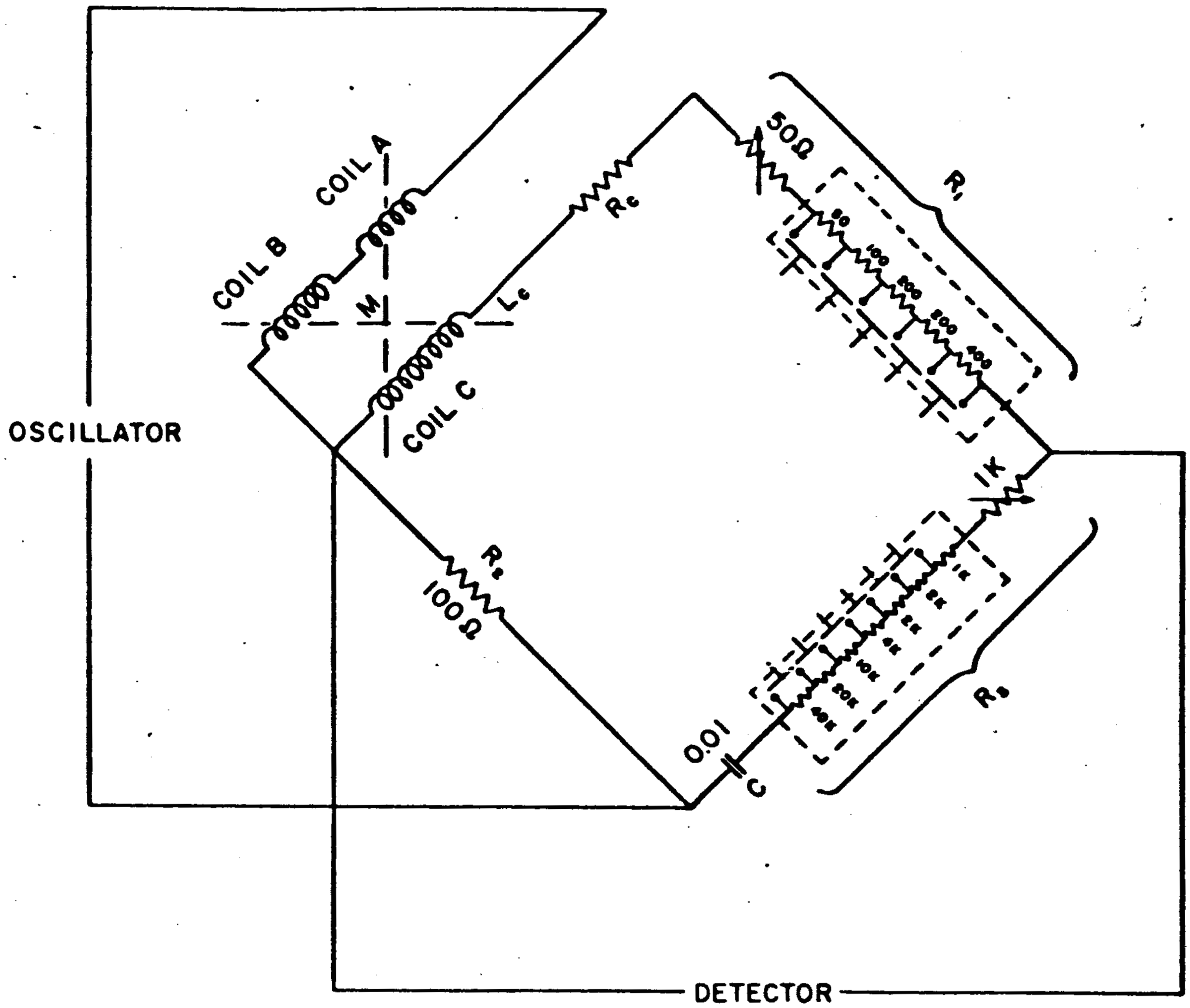

FIGURE 2

DIAGRAM OF BRIDGE CIRCUIT

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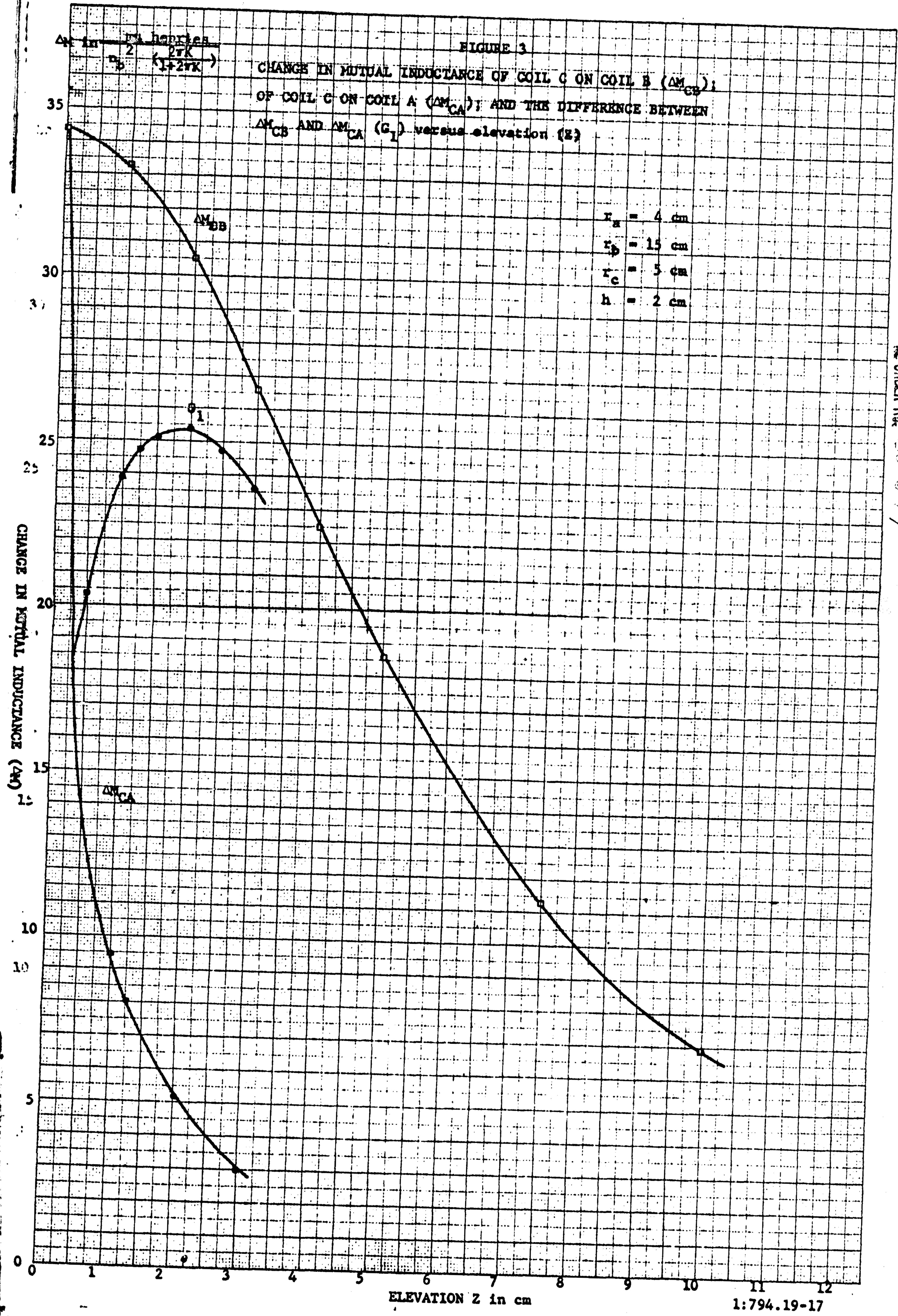
ΔM in $\frac{n_a}{n_b^2}$ henries $\left(\frac{2\pi K}{1+2\pi K}\right)$
FIGURE 3
CHANGE IN MUTUAL INDUCTANCE OF COIL C ON COIL B (ΔM_{CB}); OF COIL C ON COIL A (ΔM_{CA}); AND THE DIFFERENCE BETWEEN ΔM_{CB} AND ΔM_{CA} (G_1) versus elevation (Z)
r_a = 4 cm
r_b = 15 cm
r_c = 5 cm
h = 2 cm
ΔM_{CB}
G_1
ΔM_{CA}
CHANGE IN MUTUAL INDUCTANCE (ΔM)
ELEVATION Z in cm
0
5
10
15
20
25
30
35
1
2
3
4
5
6
7
8
9
10
11
12
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21

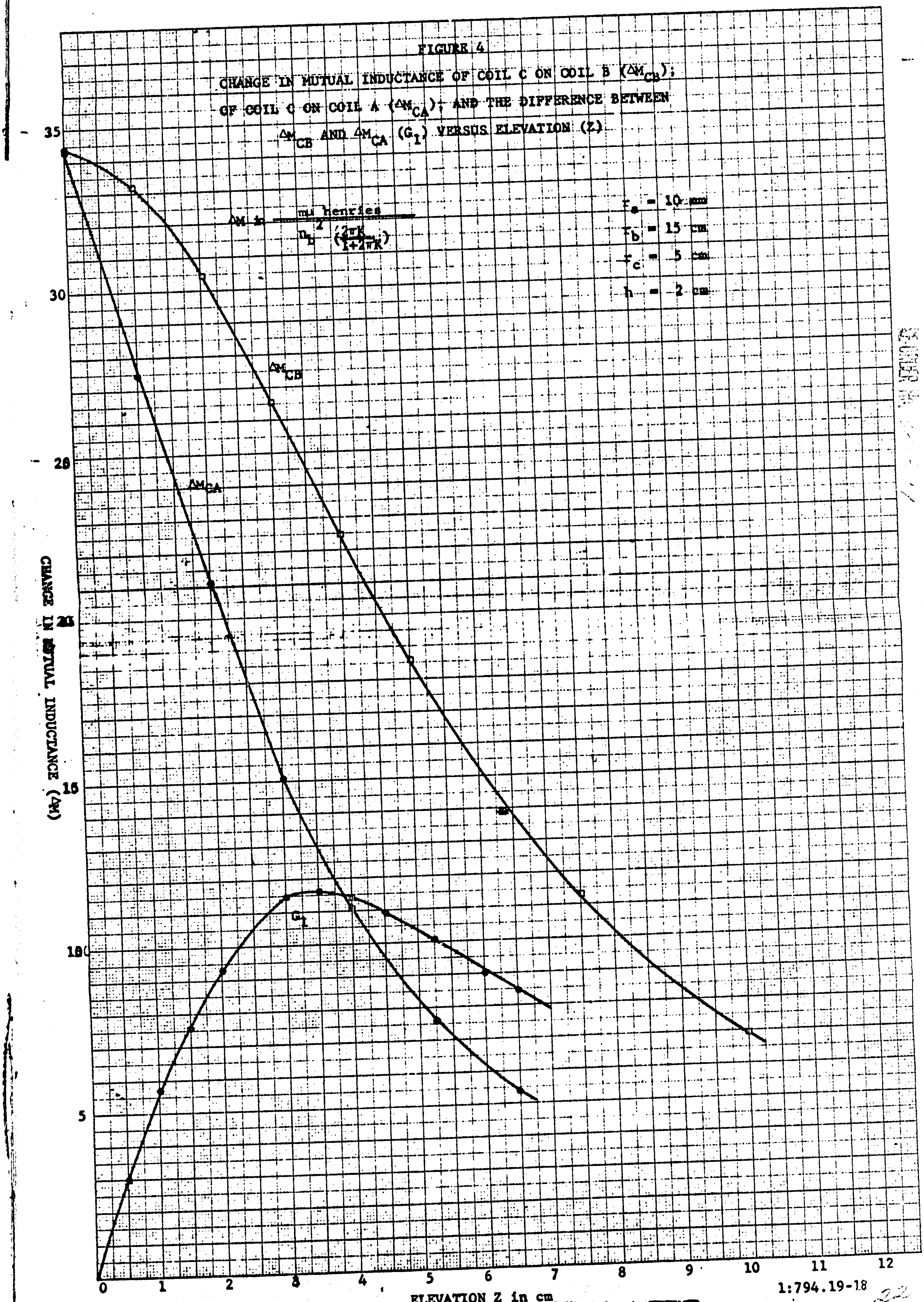
FIGURE 4
CHANGE IN MUTUAL INDUCTANCE OF COIL C ON COIL B (ΔM_{CB}); OF COIL C ON COIL A (ΔM_{CA}); AND THE DIFFERENCE BETWEEN ΔM_{CB} AND ΔM_{CA} (G_1) VERSUS ELEVATION (Z)
ΔM in $\dfrac{\text{mu henries}}{n_b^2 \left(\frac{2\pi K}{1+2\pi K}\right)}$
r_a = 10 cm
r_b = 15 cm
r_c = 5 cm
h = 2 cm
ΔM_{CB}
ΔM_{CA}
G_1
CHANGE IN MUTUAL INDUCTANCE (ΔM)
35
30
25
20
15
10
5
0
1
2
3
4
5
6
7
8
9
10
11
12
ELEVATION Z in cm

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22

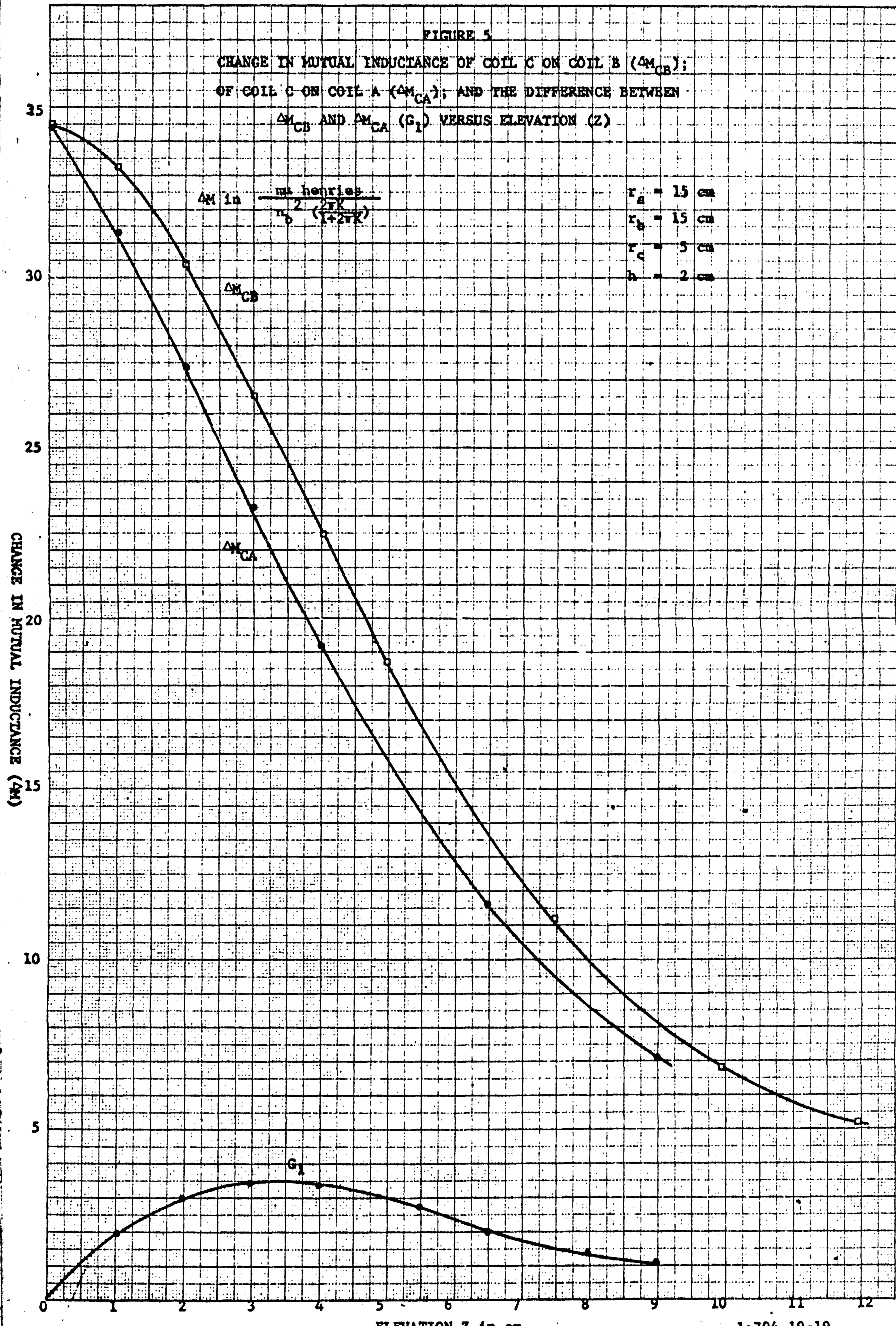

FIGURE 5

CHANGE IN MUTUAL INDUCTANCE OF COIL C ON COIL B (ΔM_{CB}); OF COIL C ON COIL A (ΔM_{CA}); AND THE DIFFERENCE BETWEEN ΔM_{CB} AND ΔM_{CA} (G_1) VERSUS ELEVATION (Z)

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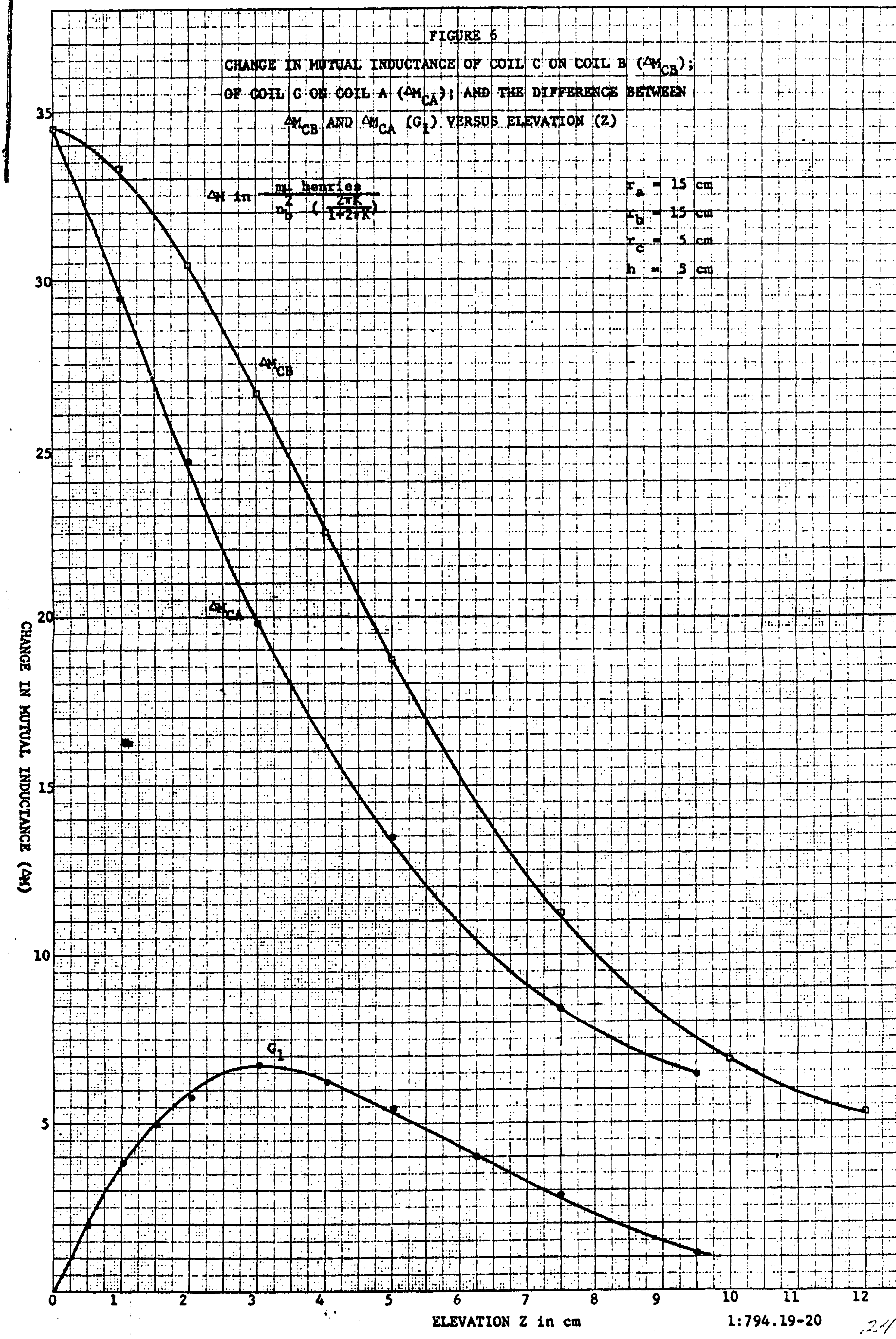
FIGURE 6

CHANGE IN MUTUAL INDUCTANCE OF COIL C ON COIL B (ΔM_{CB}); OF COIL C ON COIL A (ΔM_{CA}); AND THE DIFFERENCE BETWEEN ΔM_{CB} AND ΔM_{CA} (G_1) VERSUS ELEVATION (Z)



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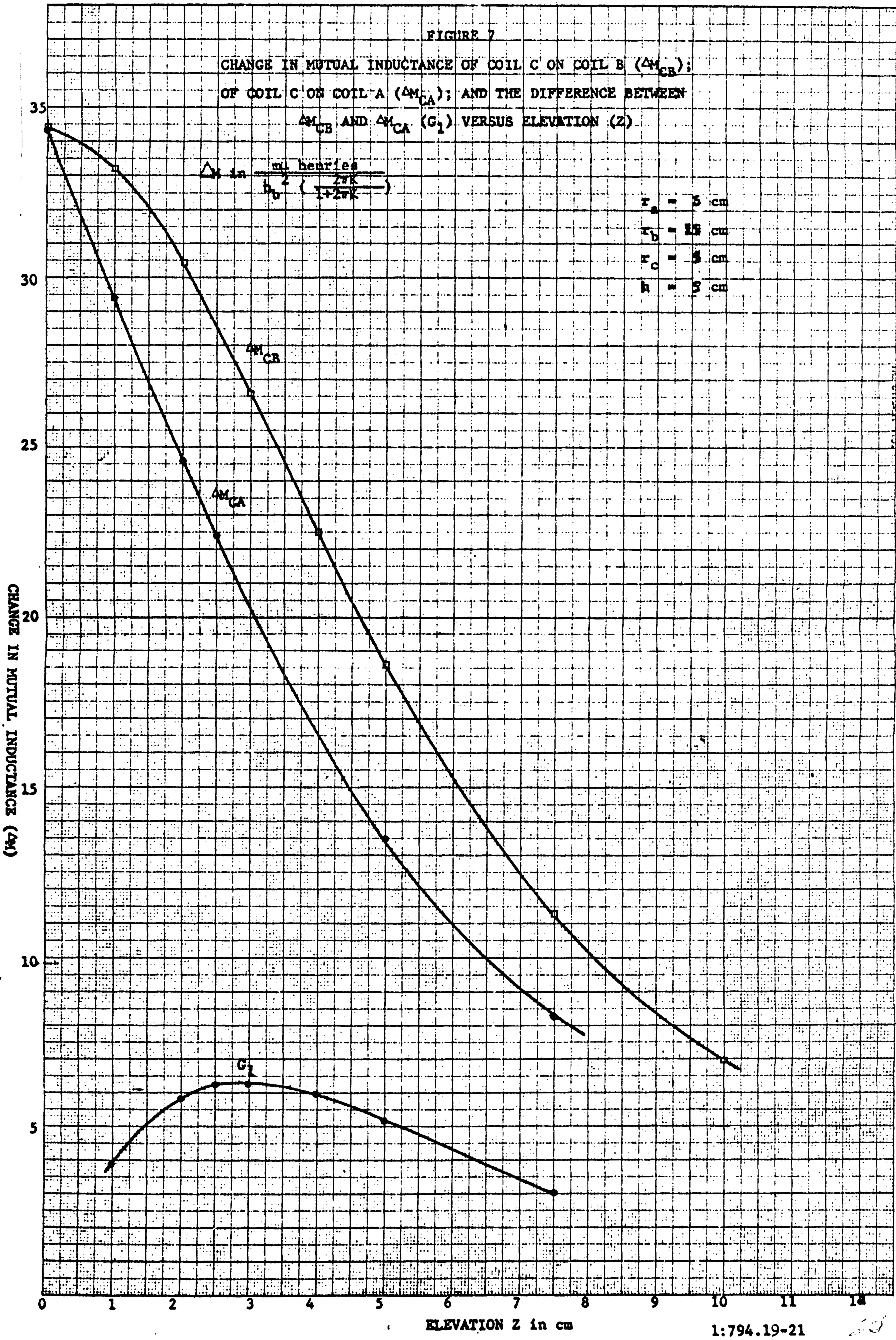

FIGURE 7

CHANGE IN MUTUAL INDUCTANCE OF COIL C ON COIL B (ΔM_{CB}); OF COIL C ON COIL A (ΔM_{CA}); AND THE DIFFERENCE BETWEEN ΔM_{CB} AND ΔM_{CA} (G_1) VERSUS ELEVATION (Z)

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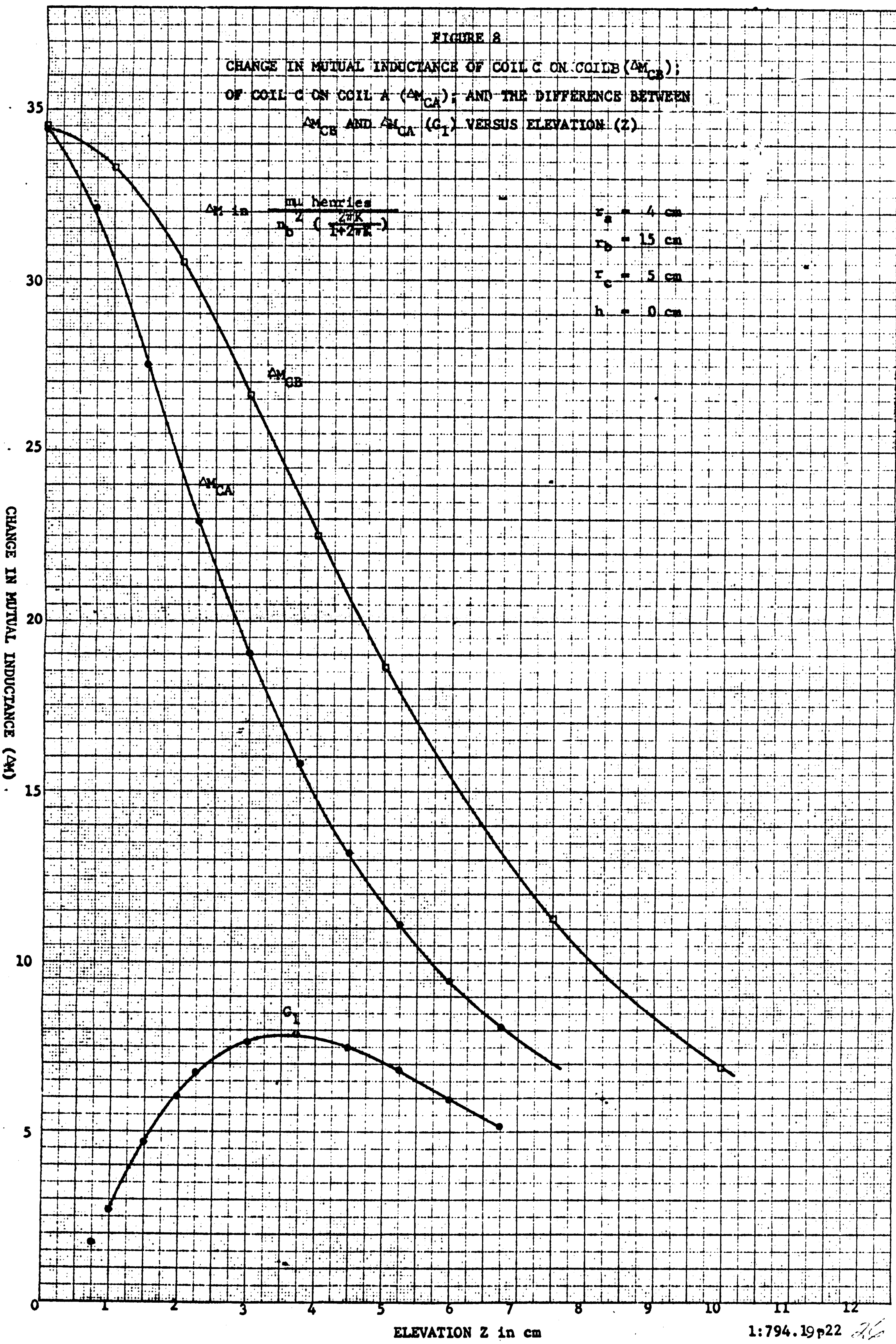

FIGURE 8
CHANGE IN MUTUAL INDUCTANCE OF COIL C ON COILB (ΔM_{CB}); OF COIL C ON COIL A (ΔM_{CA}); AND THE DIFFERENCE BETWEEN ΔM_{CB} AND ΔM_{CA} (G_1) VERSUS ELEVATION (Z)
ΔM in $\dfrac{\mu\text{ henries}}{n_b^2\left(\frac{2\pi K}{1+2\pi K}\right)}$
r_a = 4 cm
r_b = 15 cm
r_c = 5 cm
h = 0 cm
ΔM_{CB}
ΔM_{CA}
G_1
CHANGE IN MUTUAL INDUCTANCE (ΔM)
ELEVATION Z in cm
0
1
2
3
4
5
6
7
8
9
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11
12
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15
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25
30
35

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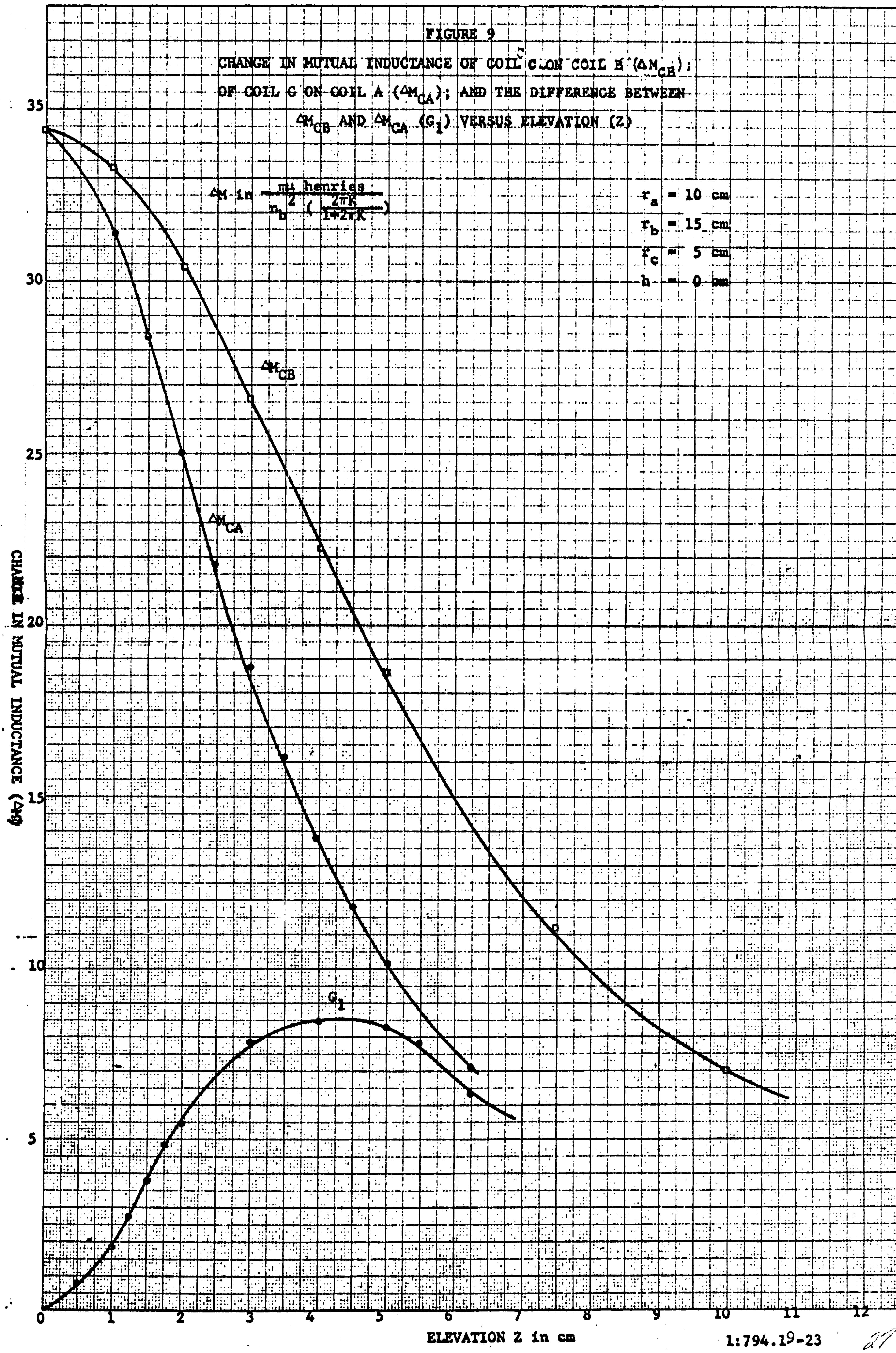
FIGURE 9
CHANGE IN MUTUAL INDUCTANCE OF COIL C ON COIL B (ΔM_{CB}); OF COIL C ON COIL A (ΔM_{CA}); AND THE DIFFERENCE BETWEEN ΔM_{CB} AND ΔM_{CA} (G_1) VERSUS ELEVATION (Z)
ΔM in $\frac{\mu \text{ henries}}{n_b \frac{Z}{2} \left(\frac{2\pi K}{1+2\pi K} \right)}$
r_a = 10 cm
r_b = 15 cm
r_c = 5 cm
h = 0 cm
ΔM_{CB}
ΔM_{CA}
G_1
CHANGE IN MUTUAL INDUCTANCE (ΔM)
ELEVATION Z in cm
35
30
25
20
15
10
5
0
1
2
3
4
5
6
7
8
9
10
11
12

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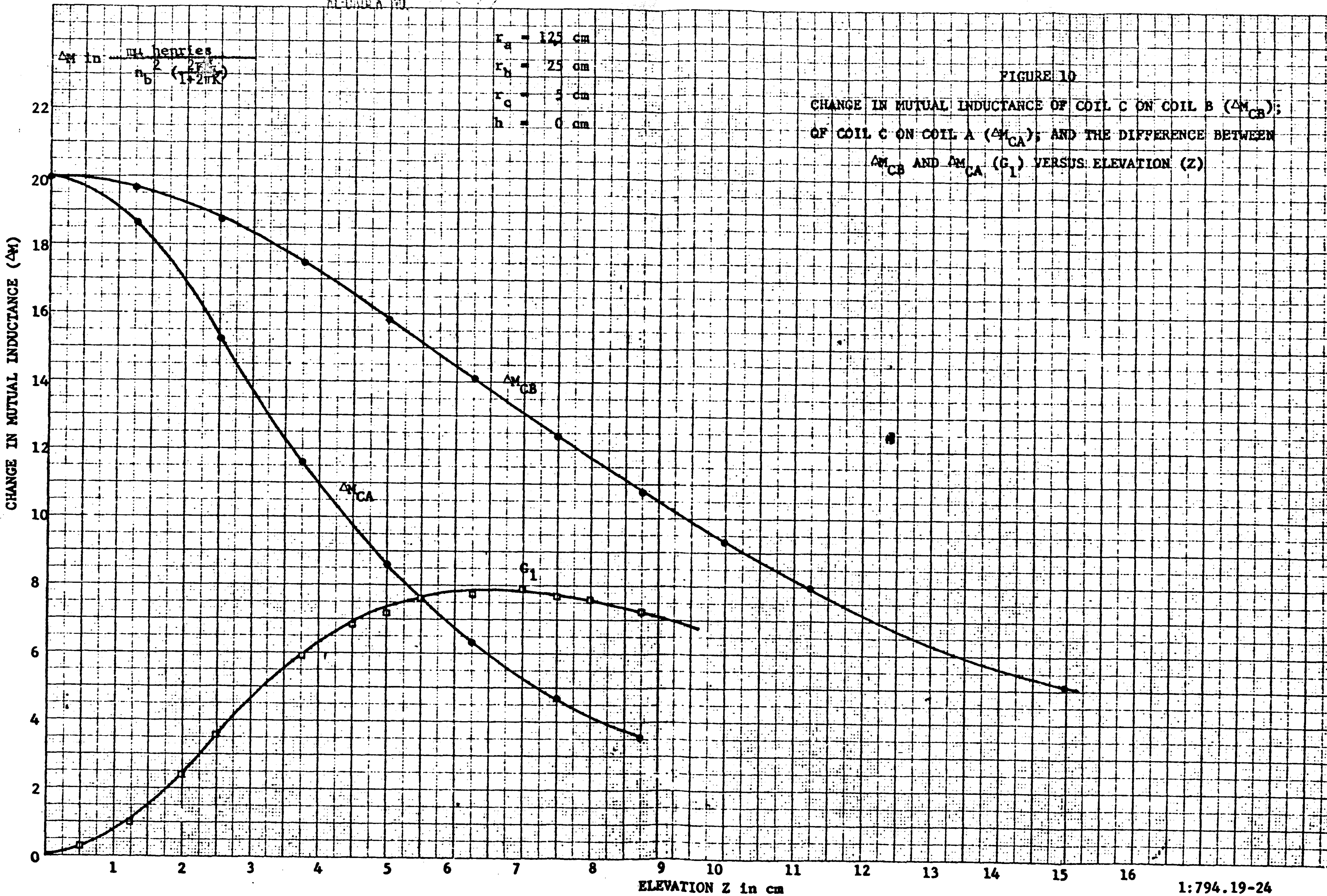

FIGURE 10

CHANGE IN MUTUAL INDUCTANCE OF COIL C ON COIL B (ΔM_{CB}); OF COIL C ON COIL A (ΔM_{CA}); AND THE DIFFERENCE BETWEEN ΔM_{CB} AND ΔM_{CA} (G_1) VERSUS ELEVATION (Z)

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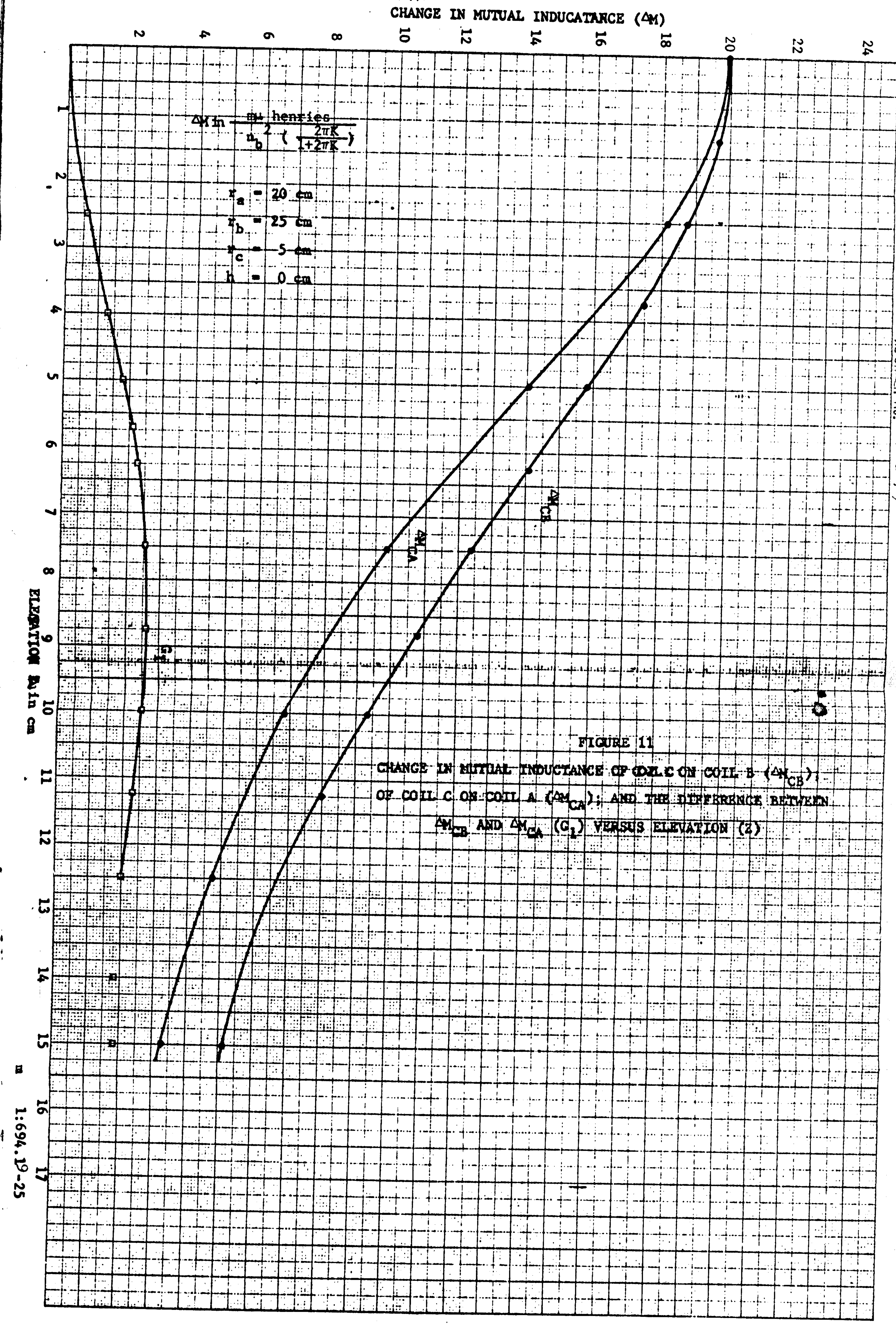
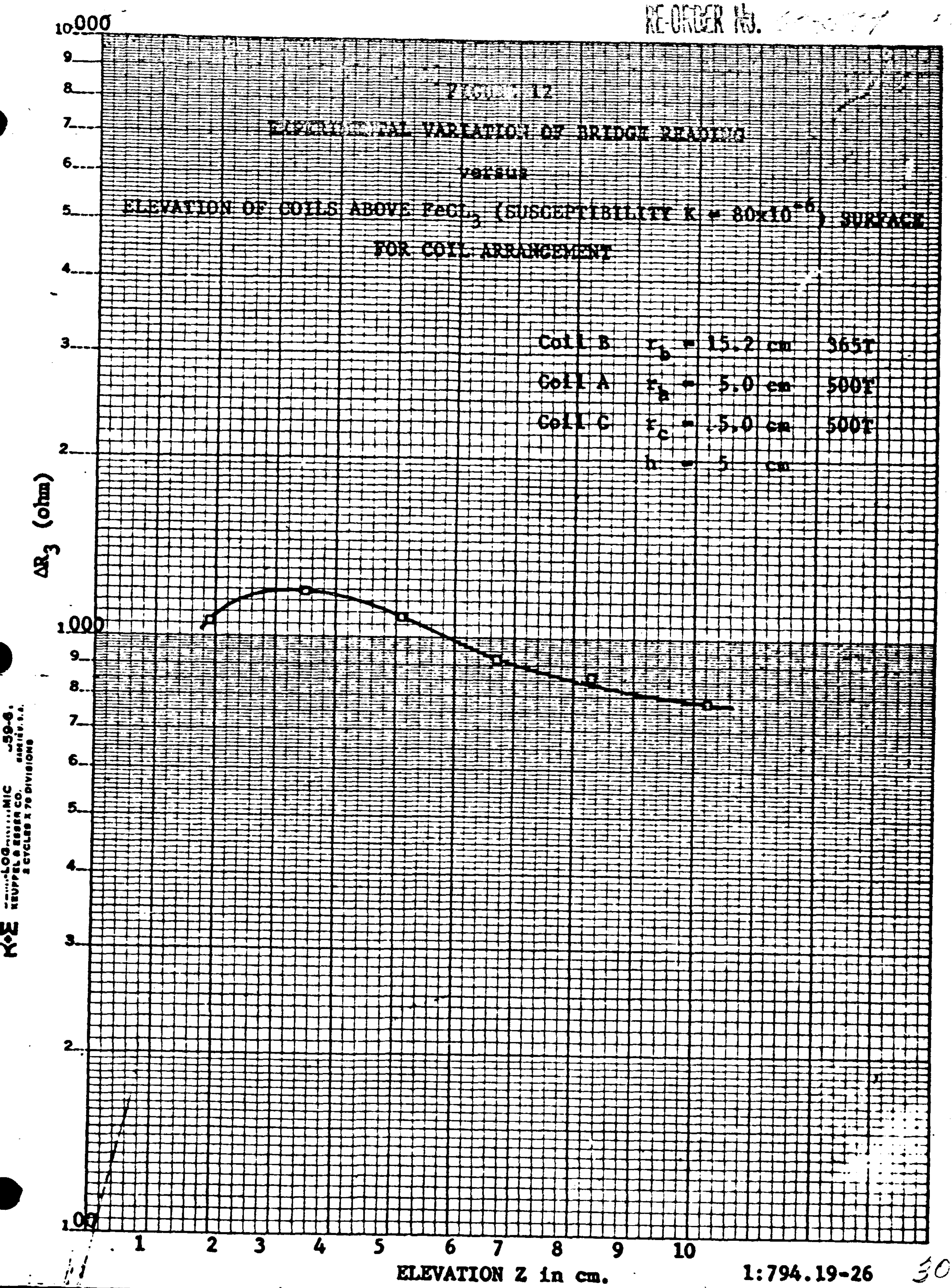


FIGURE 11

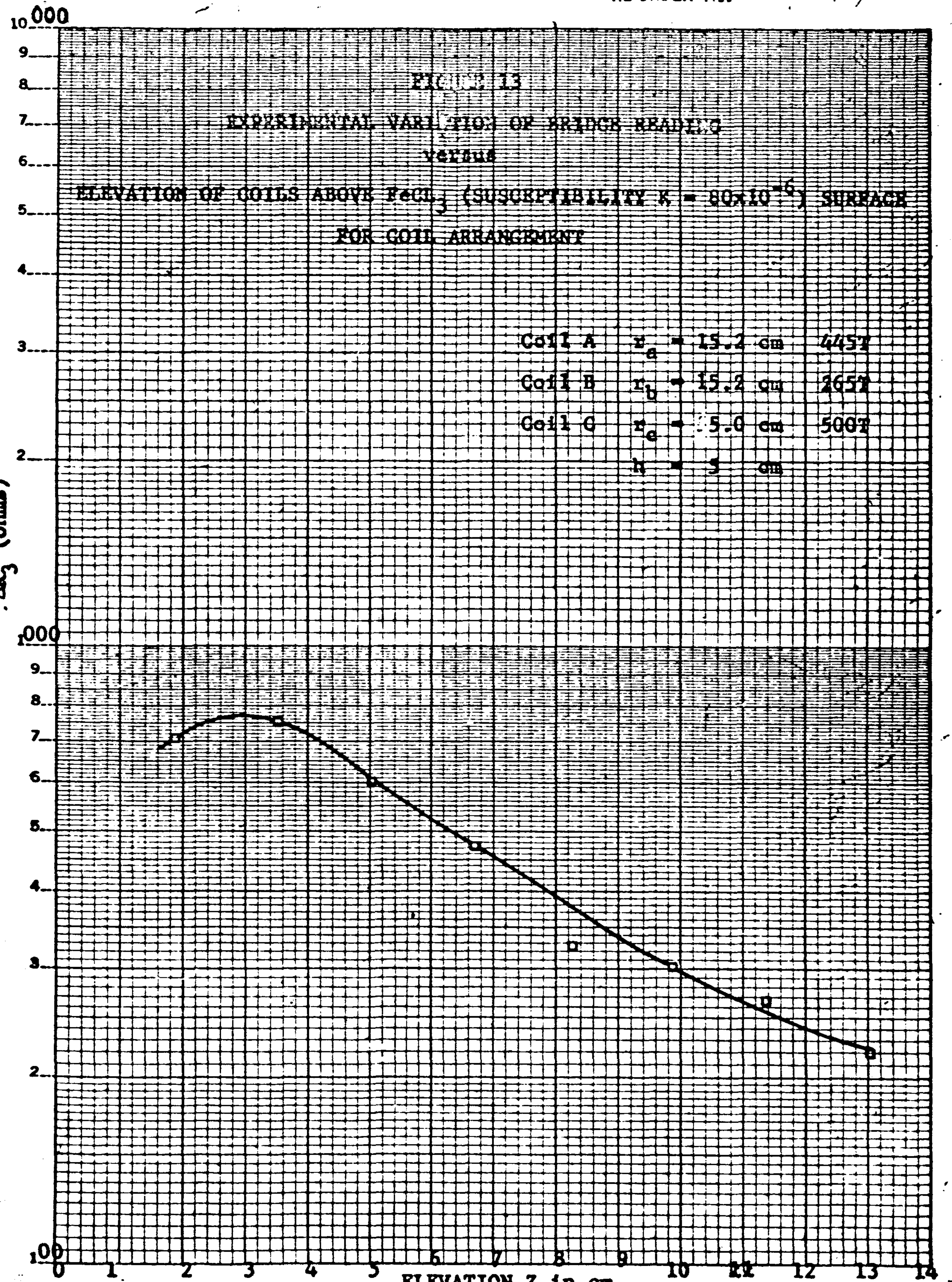
CHANGE IN MUTUAL INDUCTANCE OF COIL C ON COIL B (ΔM_{CB}); OF COIL C ON COIL A (ΔM_{CA}); AND THE DIFFERENCE BETWEEN ΔM_{CB} AND ΔM_{CA} (G_1) VERSUS ELEVATION (Z)

1:694.19-25


RE-ORDER No.
FIGURE 12
EXPERIMENTAL VARIATION OF BRIDGE READING
versus
ELEVATION OF COILS ABOVE FeCL3 (SUSCEPTIBILITY K = 80x10-6) SURFACE
FOR COIL ARRANGEMENT
Coil B rb = 15.2 cm 365T
Coil A ra = 5.0 cm 500T
Coil C rc = 5.0 cm 500T
h = 5 cm
ΔR3 (ohm)
10,000
1,000
100
1 2 3 4 5 6 7 8 9 10
ELEVATION Z in cm.
K&E LOGARITHMIC 359-6 KEUFFEL & ESSER CO. 2 CYCLES X 70 DIVISIONS
1:794.19-26

30

RE-ORDER No. 60-349



1:794.19-27